DIASTROPHISM AND THE FORMATIVE PROCESSES

XI. SELECTIVE SEGREGATION OF MATERIAL IN THE FORMATION OF THE EARTH AND ITS NEIGHBORS

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In the last number of this *Journal*[1] I endeavored to deduce from a comparison of the earth with Mars, Venus, and the moon, the order of magnitude of the total shrinkage suffered by the earth. The results proved surprisingly large. Not only that but they seemed to show that the shrinkage per unit of mass-increase became greater as the total mass grew. Since small bodies have but feeble gravitative ability to gather and hold the lighter order of molecules in a free state, it seemed probable that the moon and Mars contain higher proportion of the heavy molecules than Venus and the earth. This seemed to add emphasis to the high densities of Venus and the earth compared with the moon and Mars. It appeared to strengthen the presumption that, in this group of bodies at least, the degree of density was due to the concentrating effect of superior mass rather than original heaviness of material.

However, final conclusions were held in abeyance until the modes of organization of the four bodies could be studied with a view to detecting the probable laws of their segregation in so far as these affect the proportions of inherently light and inherently heavy materials. It is this inquiry that forms the theme of the present paper.

The subject necessarily reaches back to the genesis of this group of bodies, and the discussion will need to concern itself quite as much with the dynamic environment that influenced their formation as with the material that entered into it. The

[1] "The Order of Magnitude of the Shrinkage of the Earth Deduced from a Comparison with Mars, Venus, and the Moon," *Jour. of Geol.*, XXVIII (1920), pp. 1–17

study need not, however, go much beyond the conditions that determined the amount and nature of the material, the mode of aggregation, and its physical state. It must be specific enough, however, to touch the conditions that controlled the relative proportions of inherently heavy and inherently light material. It is therefore necessary to consider with some care the basic laws of organization of such bodies so far as these bear on selective segregation. It will save time and help toward clear treatment to give at the outset what seem to me to be the more essential principles that control the formation of cosmic bodies. It will not be amiss if these are made rather sweeping, provided they are definite enough to apply to the particulars required by our problem.

PRELIMINARY CONSIDERATIONS

While the four bodies named will usually be in mind when other bodies are not specified, there will be occasion to use certain terms in other than their commonest senses, and so let us agree upon these at the outset. By cosmic units let us understand, not simply celestial bodies, but organized bodies of any kind, whether large or small, whether "organic" or "inorganic," provided they serve a unitary function in natural processes. Let us recognize that these range from the atom, whose organization is now being pursued with a skill and success worthy of the highest admiration, up through the molecule, the crystal, the chondrus, the colloidal unit, the cell, the biologic organism, the planet, the star, the star cluster, to the stellar galaxy, at least. Let these more salient types stand for the multitude of intermediary and divergent species of divers sorts that make up the full series. Let them also stand for the unknown extensions of the series downward and upward. Let us agree that the only essential of a cosmic unit is an individualized organization which has its own material center and its own dynamic province. These organized units of course enter into varied relations with one another and form a great complex superseries, but let us consider merely the features that are common to all because essential to all. Among these essentials should appear, in their true relations, those particular features we need to apply to the solution of our special problem.

The wide range of the category thus recognized implies that the study of the organization of cosmic units is not a theme which falls solely within the province of any one of the natural sciences as we now know them; it is common ground, belonging to each and all in so far as their problems reached back into it. The biologic student of the genesis and career of the iron bacteria may invade, of his own right and to any extent that serves his purpose, the Proterozoic terranes or any other terrestrial field that promises him evidence, and we of the geological school may not say him nay, however much we may claim the province as peculiarly our own in respect to our own problems. Each particular science is best suited to make certain inquiries into the origin of organisms and of organizations, and to yield certain contributions to the common science of cosmology, using the term in its broadest sense as the science of cosmic organization, in distinction from cosmogony, which in its original sense—the birth of the cosmos—belongs to philosophy, theology, and mythology.

The cosmic systems mount up by hierarchies from what seem simpler to what seem more complex, but in ultimate analysis all, even the atom, and perhaps even the electron, are themselves complex, and the depth of such complexity is at present unfathomable. This pervasive complexity puts all in a common class and, in some sense, simplifies the common cosmologic problem, for its essence lies in finding those principles of organization that are so far essential to any organization as to be common to all.

FUNDAMENTALS OF COSMIC ORGANIZATION

I. Every cosmic unit bears a dual aspect, a material organization, and a dynamic organization. In ultimate analysis these may be merely different phases of the same fundamental entity, whatever that may be, but in their sensible aspects they are distinctly diverse. The one is very tangible and impressive and has almost monopolized attention; the other is invisible in itself and has fallen much short of the recognition it deserves as an essential element in every cosmic organization. The first is too familiar to need emphasis here; the second requires all the emphasis which a neglected essential can well receive.

II. The material factor of every cosmic unit is not only pervaded internally but is surrounded by a field of force, dominantly attractive but partially repellant. In the present study, the sphere of dominating attraction—the sphere of gravitative control—will, for brevity, usually be spoken of as though it alone represented the dynamic element of the dual organization, for it is chiefly the outlying field of gravitative control that functions actively in the selective segregation of material in the formation of cosmic bodies.

The extreme theoretical reach of gravitation is indefinite, but within a certain portion of this indefinite field, the attractive force of the particular body under study is sufficient to give it immediate control over bodies inferior to itself, unless they carry kinetic energy of their own in sufficient amount, and properly directed, to insure their escape. This field of superior force constitutes the body's sphere of control.[1] It is necessary to note that this control is merely *immediate* control; there are usually, perhaps always, higher types of control which hold ulterior sway over these, but this superior sway is exercised in such a concurrent way as not to prevent the immediate control essential to the minor body as a condition of its own existence and perpetuity. These higher controls may spring from some single more massive body or from some composite organization, as a star group. The superior spheres of control envelop the minor spheres of control; thus the moon's sphere of control revolves within that of the earth; the earth's sphere of control revolves within that of the sun; the sun's sphere of control revolves within the sphere of control of the "local cluster" of stars, and this in turn within the sphere of

[1] The recognition that cosmic bodies are surrounded by spheres of gravitative control is not at all new but merely neglected; Laplace worked out "the spheres of activity" of the planets—here called spheres of control to avoid confusion with the indefinite outward extension of the influence of the cosmic body. The spheres of control of the planets have been worked out more recently on a different basis by Moulton (*Popular Astronomy*, No. 60, May 15, 1899). The spheres of equal attraction, a different matter, have been worked out by the senior Asaph Hall (*Popular Astronomy*, April, 1899). The concept of a sphere of control is herein given a wider application than is common, and is assigned an essential function in the organization and maintenance of cosmic bodies. The concept is regarded as a helpful means of research, particularly as an aid to visualization.

control of the stellar galaxy. The sphere of control of the atom enters into the sphere of control of the molecule, and that into higher orders in succession up to the earth and beyond. The whole cosmic scheme seems to be a system of such hierarchies whose limits in either direction are unknown.

III. The dynamic value of each sphere of control dies rapidly away from the mass in which it centers to its outer border. Not only this, but each sphere of control that revolves within a superior sphere of control is larger or smaller, more effective or less effective, according to its position within such superior sphere of control. It is likely to be either increasing or diminishing as the body in which it centers swings through its orbit. If it were made to constantly approach the controlling body, its extent and efficiency of control would grade entirely away to extinction before such superior mass was reached.

IV. In such spheres of control as center in single great masses, the differential pull of the controlling mass becomes so great relatively, in its innermost portion, that bodies of a minor order intruding upon it are liable to be disrupted. When the approaching minor bodies are gaseous, their spontaneous tendency to dispersion insures their dissipation. When they are solid, the degree of fragmentation to which they are subject is likely to be limited to certain sizes, for as the fragments grow small the strength of their cohesion increases relative to their mass. Cohesion is not likely to be important in large bodies because they are usually self-compressed and hot within to such a degree that their tendencies to expand, when pressure is relieved, usually surpass their coherence.

The outer border of the disruptive zone is known as the Roche limit. Its determination by Roche was based on an ideal homogeneous fluid satellite approaching an ideal homogeneous fluid planet of equal uniform density, cohesion being neglected. He fixed the limit of disruption at 2.44 times the radius of the planet.[1] This limit is in close accordance with what seems to be the realized result in the case of Saturn's rings which stand as the classic example of minute division and distribution in response to this disruptive effect. The mathematical conclusions of Roche were amply

[1] Edward Roche, *Memoirs de l'Académie Montpelier*, I, p. 243.

supported some years later by the studies of Clerk-Maxwell,[1] and their common results were afterward verified by the spectroscopic observations of Keeler, who demonstrated that the rings are formed not of gas, as once supposed, but of discrete particles revolving in independent orbits, in other words are minute satellites or satellitesimals. From a recent study of the albedo of the rings, Bell has concluded that the largest masses in them probably do not exceed three meters in diameter—at least they are not more than a few meters across—while the majority of the visible particles are very much smaller, ranging down to the dimensions of wave-lengths of light.[2]

For the immediate purposes of our study, the important point is not so much that bodies entering this zone of disruption either from without or within are reduced to relatively small particles, though this is important, as that these conditions of stress from the controlling body stand in the way of the organization of any new body within this zone. So far as the aggregation of independent bodies of any notable mass is concerned, this is an inhibitive zone. Considered with reference to the controlling body, it may perhaps be said to be a protective zone, tending to preserve its isolation, independence, and undivided sovereignty.

In view of uncertainties as to the precise qualifications the Roche limit might require in the case of a rotating nebular spheroid, Moulton worked out a limit of similar nature but on a different basis, the purpose of which was merely to fix a more certain limit within which the organization of nebulous matter would be inhibited.[3] This limit was placed at 1.38 times the radius of the nebular spheroid, or a little more than half the radial extent of the Roche limit.

V. Accepting as a working basis the Newtonian doctrine of the unlimited penetration of the force of gravitation, it is a logical deduction that all space is under the immediate domination of

[1] "On the Stability of Motion of Saturn's Rings," *Scientific Papers of James Clerk-Maxwell*, Vol. I, pp. 288–375.

[2] Louis Bell, "The Physical Interpretation of Albedo, II. Saturn's Rings," *Astrophysical Journal*, L (July, 1919), pp. 1–22.

[3] F. R. Moulton, "An Attempt to Test the Nebular Hypothesis by an Appeal to the Laws of Dynamics," *Astrophys. Jour.*, XI (1900), pp. 122–26.

some dynamic organization or some combination of such organizations, except perhaps that theoretical neutrality may arise momentarily on the border lines of spheres of control where exact balancings of attraction may obtain for an instant; but as all celestial bodies are moving relative to one another this can only be transient and unimportant. The concept of such pervasiveness of stress throughout all cosmic space has the merit of dismissing from serious consideration certain inherited notions, for example, that somewhere in space there may be regions where "primordial" matter may have lurked in idleness from a supposed beginning, or where nebulous matter, or dissipated particles of any sort, may somehow assemble purely under their own attraction and later drift into the active cosmic world as quasi-primordial matter, and similar notions that seem to be but reshaped vestiges of oriental concepts of primitive chaos. A much more important function of the deduction, however, is its amplification of the doctrine of dynamic encounter.

VI. From the preceding generalizations it follows that the spheres of control of cosmic bodies are either perpetually plowing through the higher orders of spheres of control that envelop them, or are impinging upon other spheres of control of their own type. In either case, their own domains, as well as those of the bodies with which they interact, are perpetually suffering encroachments. Innumerable dynamic encounters of widely varying types and moment thus spring from cosmic movements. As an incident of these innumerable encroachments of one domain upon another, transfers of the minuter class of units from the field of dominance of one controlling center to that of another are almost perpetual occurrences. They constitute a system of exchange of the first order of extent and seem to be a vital factor in cosmic life. In the case of the earth, revolving in the sphere of control of the sun, this system of exchange is regarded as having a very high order of importance in the maintenance of our atmosphere and the increase of our hydrosphere.

Since encounters of some order of importance are almost infinitely frequent, it is necessary to specify explicitly the nature of the encounter in any argument that is based on frequency of

encounter. Furthermore, in determining the frequency of a given class of encounters, it is not sufficient to postulate an artificial case convenient for computation, for actual cases usually involve a natural selective adjustment of associated bodies with reference to one another. And further, the present deployment of stars may not be identical with that of earlier ages. And still further, if the frequency has for its criterion a given effect or is to be considered with reference to a given effect—explosive action for example—susceptibility to such effect is as important as the nature of the encounter. These requirements are commonly neglected.

VII. All cosmic organizations seem to be the products of opposing elements. The balance between these opposing factors seems to form the critical issue on which their endurance depends. These opposing factors vary with age, state of growth, environment, and other conditions. Out of these variations of balance arise stages of increase and depletion, of partial or total disorganization and regeneration. The history of the cosmos seems to be essentially a succession of cycles arising from either internal or external disturbances of balance. Interestingly enough, the atom happens just now to afford one of the best illustrations of internal disturbance leading to transition in organization. Thought until recently to be beyond the utmost resources of disintegration, it is now known that some of the heaviest atoms are undergoing "spontaneous" disorganization. By way of offset for the old error, as it were, the dictum now is that no known device, appliance, or force can stop this disintegration. Future inquiries will probably disclose the golden mean between these extremes. In spite of all disintegrating influences, the integrity of atomic organization, in the main, is maintained to an extraordinary degree. In the larger cosmic world there are intimations of analogous "spontaneous" disintegrations standing over against similar persistency. The eruptivity of the sun, on which the planetesimal hypothesis is founded, is revealing striking analogies to the partially disintegrating atom as will be detailed later. Some of the great hot stars give intimations of a very delicate balance of internal forces. Over against the enormous concentrating force of gravity and its allies, stands the scarcely less potent alliance of the forces of dispersion. These

latter seem, on the whole, to be overmatched by their opponents, as implied by the very existence of the stars; and yet the forces of dispersion are clearly successful in particular ways, as, for example, in the matter of radiations and in some loss of high-speed molecules and of electrons.

In this state of wavering balance between internal contending forces, those great seething bodies are plunging at high velocities through what, in a material sense, is an approximate vacuum, but what, in a dynamic sense, is an approximate plenum, a plexus of lines of force of almost infinite complexity. They are thus speeding through a perpetual succession of contingencies of external disturbance. Their hold upon their own material hangs on the perpetuated superiority of their concentrative forces, expressed typically but not wholly in their spheres of gravitative control over their dispersive forces. If the controlling spheres are invaded in a shallow way there is likely to be only trivial loss; if they are invaded deeply, serious disintegration is the logical effect. It is important to note that this disintegration is a joint effect, as much due to the approximate balance of the internal forces as to the disturbing power of the external forces.

And so in dealing with phenomena of this class, it is not more important to inquire into the direct action of the external agencies than into the state of balance of the powerful forces within these supremely active organizations themselves. This is the more imperative because there is growing reason to believe that certain orders of stars are at or near the limit where growth in mass is overmatched by concurrent growth in dispersive forces. If this belief is well founded, such nearly balanced giants of the skies may be regarded as peculiarly susceptible to disturbances of equilibrium arising from the intrusion of foreign dynamic influences into their domain, or perhaps equally their own penetration into areas of concentrated stress arising from special marshallings of other great bodies.

These considerations are deployed at some length here because the stellar conditions that render dynamic encounter effective are too commonly overlooked, and because these conditions are vital in considering cosmic disorganization which in turn is regarded as a step necessarily precedent to cosmic reorganization.

VIII. There is pressing need for rectified concepts of cosmic time and stellar endurance. The recent deep penetration of the stellar field by improved instruments, increased skill, and new methods has forced a revolutionary enlargement of concepts of interstellar space, while co-ordinate enlargements of concepts of cosmic time have not kept apace. And yet time and space are necessary correlatives in stellar movements and in stellar organization. Time concepts must keep pace with space concepts if consistent views of organizing processes are to be entertained. Inadequate concepts of time retained from old estimates of the sun's longevity and like sources now embarrass the free acceptance of cosmic views—if these imply great intervals of time—much as they restrained geological interpretations during the last century. It may be wholesome therefore to inquire specifically: What length of life is implicitly assigned to stars when they are made integers in the evolution of a globular cluster or of a galaxy? What intergenetic periods mark off the generations of stars? What careers appropriately fit them into the vast cosmos that is now revealing itself? And then, subordinate perhaps to the life of a star, what intergenetic periods mark off the generations of planets?

It is to be recognized, of course, that the career of a planet may belong to a different order of magnitude from the career of a star, or of a star cluster, or of the galactic system, and no doubt these differ among themselves. And so our immediate problem may not be more than remotely concerned with these immense questions, but yet it is related to them, and its answer should be consistent with them. Perhaps all that need be said here is that when the estimates of the longevity of stars, star clusters, and the stellar galaxy are brought into harmony with the time requirements of their own processes of organization and their own normal careers, students of the evolution of our little planet will probably feel quite as much call to amplify as to repress their interpretations of the terrestrial time factors in order to bring them into harmony with those of the higher systems.

IX. As a matter of scientific conservatism, it should be taken for granted that the sole source of material and of energy for the formation of new organizations is to be sought in the dissolution

of pre-existent organizations. In most cases, if not in all, however, the dissolution of such previous organizations is not ulterior dissolution; it is usually only the disintegration of one order of organization into elements of a somewhat lower order. Neither dissolution into chaos, in any strict sense, or into ultimate factors, nor generation from chaos or from ultimate factors or from anything that is absolutely new, seems to have any naturalistic warrant so far as present cosmic processes are concerned. Nor is there much more warrant for bringing into play any really unknown force or agency, though the discovery of new ways of action of known forces and agencies is to be expected. Scientific inquiry in genetic lines appears therefore to have for its appropriate field of study little else than partial disorganization followed by corresponding reorganization, though not necessarily of the same type, order, or extent. The scientific student therefore hesitates to call into service any material or energy which he cannot trace back to some known source.

X. In the formation of new cosmic bodies, even of the "inorganic" class, an organizing germ or nucleus, inherited from some parent organization, seems to have much the same function, and to be about as necessary as the seed or the ovum of an organism of the "organic" type. In either case the germ must apparently have both a material and a dynamic factor. This necessity appears to be chiefly due to the essential part which a collecting field of force and a retaining sphere of control play in organizing a cosmic body. In the concrete discussion to which we shall now turn, the strength and the reach of the organizing field of force will be held to be the chief criterion that determines whether dissevered or disorganized masses of matter shall reorganize as single bodies and pursue independent careers, or shall continue to be merely scattered food to be picked up by bodies already organized and endowed with effective collecting fields of force.

THE SELECTIVE SEGREGATION OF PLANETARY MATERIAL

In this discussion there will be no occasion to consider any hypothesis of the origin of the four bodies under study that has not been worked out into such definite terms as to bear specifically

on the question of the segregation of inherently heavy from inherently light material, the crux of our problem. Two postulated origins may clearly have such bearings, both of which are now familiar: (1) derivation from a rotating nebular spheroid by centrifugal separation brought into effective action by cooling and consequent acceleration of rotation, and (2) derivation from solar material ejected either spontaneously or under the stimulus of a passing body. The principles involved in these two types will probably serve to cover any other origin for which good reasons may be assigned.

While I am unable to see how planets such as form our system can have arisen from a rotating spheroidal nebula by centrifugal action, it yet seems best, out of deference to any who may still think that some view of this general type is tenable, to discuss this postulated mode of genesis in so far as it bears on our problem. It will only be necessary, however, to review the phase of the theory most dependent on the dynamic environment which controlled the evolution, for that touches the soul of the subject.

THE CENTRIFUGAL EVOLUTION OF A GASEOUS SPHEROID UNDER ITS OWN DYNAMIC ENVIRONMENT

Every organized nebula, like every other organized body, must have an adequate enveloping field of force and sphere of control as a necessity of its organized existence (I and II, above). The postulate that there was once a spheroidal nebula of the mass of the solar system which in contracting shed secondaries at various distances from its center as far out as $2\frac{1}{2}$ billion miles and yet was able to hold them then and afterward, carries the implicit assumption that it had a distinctly effective sphere of control. The shedding of the four little bodies under study took place only after the postulated nebula had shrunk to about one-twentieth of the radius it had when it displayed its effective holding power by its control over the material shed for the planet Neptune, while the outermost reach of its holding power must have extended much beyond this. At the relatively concentrated stage when the shedding of the substance for our little group of bodies took place, the inner zone of control must have grown relatively intense; the

disruptive belt just outside the rim of the rotating spheroid (IV above) must have had a notable development. If it were quite safe to assign it the full breadth of the Roche limit, which holds so well in the case of Saturn's rings, it would have had, taking the earth stage as a mean, an outward reach of 133,000,000 miles. But let us follow the safer course of using the conservative criterion of Moulton which gives a zone of 35,000,000 miles (IV above). Let it be recalled that the fragments of a disrupted mass revolving about the controlling body under the conditions of this case take orbital courses more or less parallel with one another. If the gaseous rim of the nebula could have been "thrown off" as a coherent body, it would not only have been disrupted into minute constituents, but these would have been given orbits of a type much like those pursued by the particles in Saturn's rings, all the more because the constituents of a gas tend to disperse themselves by their own interaction. This is equivalent to saying that the dynamic conditions within this zone were such as to inhibit any aggregation of this material into a common large body like the earth, Mars, or Venus, or into a lesser number of bodies of any considerable size. Even when such scattered orbital matter was left by the withdrawal of the nebula in the less intense horizons of the nebular field of force, its aggregation would still be greatly embarrassed by the superior control of the central mass. It is a common error to think of such scattered matter as though it were in neutral space entirely free from all forces except its own mutual attractions. The control of the central body so far embarrasses the assemblage of minute particles under the actual conditions of such a case as this as to render their aggregation into a single body improbable, as Moulton has so effectually shown.[1]

However, for the sake of seeing its bearings on the problem in hand, let us waive this improbability and try to follow the aggregation of the minute constituents of a quasi-Saturnian ring "thrown off" from the postulated rotating nebula.[2]

[1] F. R. Moulton, "An Attempt to Test the Nebular Hypothesis by an Appeal to the Laws of Dynamics," *Astrophys. Jour.*, XI (1900), p. 115.

[2] The deduction that the molecules shed by centrifugal action from a rotating gaseous spheroid would pass into individual orbits and form a planetesimal system does not depend solely on the Roche effect, as shown in "The Bearing of Molecular Activity on the Spontaneous Fission of Gaseous Spheroids," Publication No. 107, Carnegie Institution of Washington, 1909, pp. 161–67.

Let it be noted at the outset that the material to be aggregated was planetesimal in a very strict sense of that term. Each integer, whether it be a molecule, a particle, or any such more considerable aggregate as might be formed under the conditions of the case, was pursuing a nearly circular orbit around the central controlling body, the nebula at first, the sun later. This precisely fits the definition of a planetesimal. This means that the particles were in a dynamic, not a static state; they were under control, not free. Whatever aggregation followed was therefore of the planetesimal type, that is, particle joined particle in an individual way as their orbits and orbital forces permitted. Their orbital velocities hovered about that of the earth (18.6 miles per second) let us say, as a mean, the inner faster, the outer slower, the orbits of those equally distant from the center slightly inclined toward one another. Beside these differences of velocity and inclination—that arose from the nature of the case—the planetesimals inherited diverging courses from mutual collisions and rebounds as they emerged from the gaseous into the orbital state. To overcome these divergencies of orbit and these differences of speed and develop aggregates of one kind or another in place of the molecules inherited from the gaseous state, there were two classes of forces: (1) the collective attraction of the whole ring or disk or some bunched portion of it, and (2) the aggregating influences of individual molecules upon one another. The first would tend to make a single planet, if the whole were drawn together, or a few planetoids, if there was aggregation by bunching; the second would make at first a multitude of minute particles which would grow to larger sizes in proportion as the agencies of later aggregation proved superior to the effects of fragmentation, exfoliation, trituration, and friction in other forms after the particles had grown large enough to give these notable efficiency. Only the salient features can be touched here.

1. The ground of the first class of agencies has already been covered. No general nucleus nor any effective bunching was inherited from the nebula; indeed concentration was definitely inhibited up to the time of the withdrawal of the Roche limit. There might be, to be sure, a certain kind of transient bunching of the planetesimals in their orbits, such as affects the present planets,

but the relative rates of revolution that brought this about would destroy it. Collectively, the planetesimals would be so distributed that they would have almost no concentrating force of their own that was not later reversed or neutralized by their own orbital motions.

2. Practically the whole aggregation, then, would be that of the formation of discrete particles such as started with the joining of molecules and were built up thence into crystals, pellets, nodules, or whatever these might grow into later. The chemical combination of molecules would take place at proper temperatures readily enough by simple contact, whether this arose from collision while in the state of a gas, or from contacts brought about by planetesimal motion, or otherwise. Such refractory chemical compounds as now form the main mass of the solid bodies of the moon, Mars, Venus, and the earth, would probably be formed at high temperatures while they were still a part of the postulated nebula. The critical feature of the case lies in the way these complex refractory molecules would be gathered together after they were formed. While they remained in a free state as molecules they would normally tend to rebound on collision as molecules do and so maintain their free state. Even if they were brought together under conditions favorable to remaining together, their rotations or vibrations would tend to throw them apart, as would also subsequent collisions. To overcome these adverse influences, there was need for some special uniting agency, as is well recognized in the familiar case of the formation of the globules of fogs and clouds from water vapor in the atmosphere. It was long supposed that there must be a dust particle or some similar aggregate to serve as a collecting center (the "seed," X, above); but it was later found that molecules electrically charged serve this function also. In our problem, the formation of the first minute aggregates is the very crux of the question, and we cannot assume the existence of any such dustlike aggregates as the means of starting the process. But molecules electrically charged would probably be freely developed by friction, by the action of ultra-violet light, and by other means, and such charged molecules might well serve as the "seed" for starting the minute aggregates.

How far would such aggregation be likely to go, as a rule? There is no need to consider exceptional possibilities, for our problem relates to the common average result. The attraction between two molecules oppositely charged is many billion times greater than their gravitative attraction[1] and may be large compared with the inertia of their relative motion. Charged molecules might then serve as very efficient centers for the gathering-in of molecules, as also very small particles. But an electric charge is confined to the surface of a particle, which increases as the square of its radius, while gravitation varies as the mass which increases as the cube of the radius. And so, after a certain amount of growth, the charges carried on the particles would have less attractive power than the masses into which the particles had grown. But a more important practical consideration lies in the fact that electric charges of like kind repel one another and thus limit the total charge likely to be gathered on a given mass under natural conditions; for example, any electric charges which a forty-pound bolide would probably pick up naturally would lend little aid in gathering in other forty-pound bolides to form a forty-ton bolide. There is thus an obvious limitation to the range of effective electric aggregation, however efficient it may be as an originating agency. A beautiful illustration at once of such effective aggregation and of its limitation is presented by the formation of snow crystals from vapor in the air. These form and grow with great facility up to a certain size when the temperature of moist air falls below the freezing-point; but after a certain moderate growth, the limiting and adverse conditions increase in relative efficiency and arrest further growth; not infrequently it is reversed.

In the case of cosmic particles probably the most effective preventive of indefinite growth is the friction and collision of the masses, themselves. As the particles grow into nodules of notable size and mass, their cohesion is less effective relative to their moving force, and they more readily go to pieces on impact. Trituration and other lesser effects of moving contact would be more frequent

[1] R. A. Millikan, in a personal communication, states: "The attraction of two opposite electric charges is 10^{27} times as great as the gravitative attraction of two atoms of hydrogen."

and perhaps more effective on the whole than fragmentation. This would quite surely be true of the minute particles. According to the interpretation of Bell,[1] a milling process of this triturative sort has proved very effective in reducing to minute sizes the satellitesimals of the Saturnian rings. When masses of any considerable size were reached, probably exfoliation from the effects of rotation in the unscreened rays of the sun would give rise to flaking and thus prepare new matter for the milling process.

On the other hand, if magnetic particles were much developed, it is probable that their special attraction would aid in building up masses, so far as the supply of such material went. Probably such malleable substances as iron, nickel, and the other metals would weld rather freely by impact. Metallic particles might thus unite nearly to the extent they were permitted to come into collision. Such stony substances as brought crystalline or concretionary forces into play would probably build up more readily than other matter and more effectively resist destructive agencies afterward. But it must be noted in all these cases that as the molecules were more or less heterogeneously mixed originally, the opportunities for assembling homogeneous matter to form aggregates of any one kind would have natural limitations.

The logic of the case, taken all together, seems to lead to the conclusion that aggregates arising under these ideal planetesimal conditions would be limited to small sizes as a general rule. This is in harmony with the results realized in the Saturnian rings, and also in the zodiacal planetesimals to be more fully discussed in the next article. It is also in harmony with the dimensions attained by the chondri and chondrules that form characteristic constituents of 90 per cent of the stony meteorites. These range in size from a walnut down to spherules of dustlike minuteness.[2]

The point of most critical importance to our inquiry is the effect on selective action introduced by these growths so far as they went. In the first place, all such matter as continued in a free molecular state, whether aggregated as gases or deployed as planetesimals, would not be gathered about these small aggregates

[1] *Loc. cit.*

[2] O. C. Farrington, *Meteorites* (1915), p. 102.

by their own gravitative power. Incidentally molecules might be entrapped or occluded within these small bodies, or chemically united with them, or possibly even held against them by surface adhesion; but, otherwise, free molecules would rebound and escape control. Those solid particles that were highly elastic would also largely escape by rebound; those that were inelastic would more largely remain adherent after impact. Malleable substances like the metals would be likely to weld and cohere by collision. In general, these cohering bodies belong to the heavier order of substances, and so bodies formed in this way would be for the greater part selectively heavy.

If we could be sure that the chondrules of meteorites represent accretion of the foregoing type—a hypothesis to be seriously considered—it would give a specific insight into the cosmic aggregates of this order, for then they might be said to be dominantly formed of ferro-magnesian silicates, nickel-iron, and metallic sulphides, but it would be premature to draw this conclusion.

At any rate, since, on the one hand, these small bodies could not hold free molecules of the lighter order, and, on the other hand, the conditions were favorable for the aggregation of metallic substances, heavy silicates, sulphides, and so forth, it seems safe to conclude that *these small aggregates contained a relatively high proportion of inherently heavy matter.*

It seems to follow then that, if Mars, Venus, the earth, and the moon could have been gradually built up by the assemblage of particles, crystals, pellets, nodules, or even more considerable masses formed in this selective way, the percentage of heavier constituents could scarcely have been less in the earlier stages and in the smaller bodies than in the later stages and in the larger bodies, while they were probably somewhat distinctly greater; for in so far as these bodies succeeded in becoming large, they could then, but only then, have held the lighter order of molecules in a free state and thus have reduced their mean density. When atmospheres and hydrospheres were thus added, the processes of oxidation, hydration, and carbonation became important and the groundwork was laid for petrological derivatives from the products of these processes. A large class of the rocks and minerals of the outer

part of the earth, which usually have rather low specific gravities, are probably wholly dependent on the presence of the atmosphere and hydrosphere at the time of their formation. And so, if the moon, Mars, Venus, and the earth, could have been built up in this way, the moon should have the highest percentage of heavy material and the others should follow in the order of their masses, atmospheres, and hydrospheres. But it was previously shown that the conditions were very adverse to the building up of these four bodies in this way and there is no likelihood that they had such an origin.

It is perhaps worth while to add that, even if we were wrong in concluding that the planetesimal aggregates would be small, the result would be little different in density or in physical state, for as the aggregation of the particles in their orbits proceeded, the resulting aggregates would become more widely separated and further aggregation would take place only at correspondingly longer intervals. There would be little change in the kind of material or in the heat effects. The material would be a little more bunched before infall, but the bunches would be more scattered in space and successive infalls more distant in time. Precipitate aggregation is quite out of the question under these conditions.

As remarked at the beginning of this section, the material discharge from the rim of a rotating spheroid of gas by centrifugal action should form an ideal system of planetesimals, and so the method of their growth may be taken as a type of such action where the molecules are given subparallel orbits from the start and there is no commanding nucleus to gather them into bodies of the planetary order.

If this analysis is correct, it will be seen that the chance of developing a molten earth from a rotating gaseous nebula by centrifugal separation is about as remote as could well be imagined.

THE SELECTIVE SEGREGATION OF MATERIAL UNDER THE PLANETESIMAL HYPOTHESIS

The particular form of the planetesimal hypothesis which has been most fully worked out and tested postulates that the material of the planets was derived from the sun by means of its own

ejective activity stimulated to special intensity by the differential attraction of some passing body. Two essential factors are involved: (1) the ejection to the requisite distance of the requisite matter—only a fraction of 1 per cent of the sun's mass; and (2) the addition of sufficient transverse momentum to cause the ejected matter to revolve about the sun. The latter is the more critical factor, for the eruptivity of the sun is known to have such a high degree of efficiency, even at the present time, that only a relatively slight increase is required to project the small fraction of the sun's substance to the distance of the planets. Such projections would, however, fall back to the sun, unless they were given a transverse motion by some agency other than radial projection. A passing star or other body has been postulated to meet this requirement. The tidal stresses developed in the sun by such passing body would stimulate eruptivity and give direction to the projections while the pull of the passing body would draw the ejected matter into orbital courses.

In about a half-hundred cases worked out mathematically by Moulton to test the validity of the postulated effects, a star of medium size passing at from one to five astronomical units' distance was taken as the parent of the orbital motion; its diverting competency was found to be unexpectedly effective.[1]

Later it was suggested that a much smaller body—passing however much nearer to the sun—might serve as well to give both the tidal stimulus and the transverse motion required, but this has not yet been worked out mathematically.[2] Still more recent studies have led to the belief that there is a wide range of possibilities respecting the co-operating body, as will be specified later.

RECENT DISCLOSURES BEARING ON THE SOLAR PARENTAGE OF THE PLANETS

Respecting the projectile power of the sun, important light has been shed by very recent discoveries. Remarkable eruptions of the sun took place on May 29 and on July 15, 1919. A fine series of spectroheliographic photographs were taken at the Yerkes

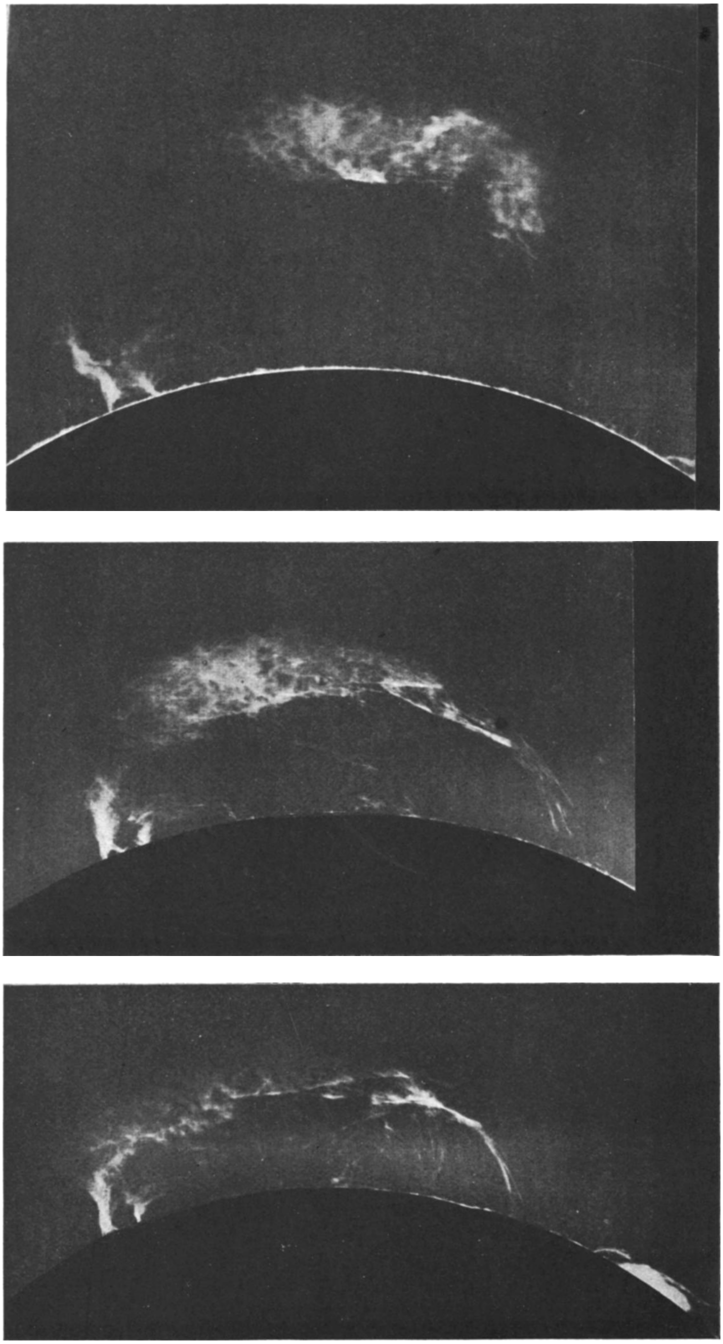
[1] *Carnegie Year Book*, No. 5 (1906), pp. 166 and 168.

[2] *The Origin of the Earth* (1916), p. 118.

Observatory by Pettit and associates.[1] These disclose motions of quite an astonishing nature. Fortunately for our purposes, the photographs were taken with one of the calcium lines, and as calcium has the atomic weight 40 and enters widely into the constitution of the earth body, its projection in this effective way has more significance than if it were one of the lightest elements. The general facts of the two cases are shown by Plates I and II, reproduced here from Plates IV and VI of Pettit's article. Both eruptions gave rise to archlike forms. The apex of each arch vanished while it was still ascending, the first disappearing at a height of 760,000 km. above the surface of the sun, the second at 720,000 km., that is, at heights somewhat more than the radius of the sun in each case. At the time of disappearance the first had an ascensive velocity of 60 km. per sec., the second, 163.9 km. per sec. Perhaps the most remarkable features disclosed were suddenly increased rates of ascent taken on at intervals, while the rates of ascent between these stages of increase were essentially *uniform*. Thus in the eruption of May 29, there was a rise, for 50,000 km., from a point 150,000 km. above the surface of the sun at a rate of 5.5 km. per sec., when the rate changed to 9.2 km. per sec., which was maintained for 119,000 km., when the velocity again changed to 27.9 km. per sec., which was held for 91,000 km., when the rate again increased to 60 km. per sec., which was maintained for 230,000 km. and was still being held when the prominence vanished, doubtless either by cooling or dispersion or both. In the eruption of July 15, it was found that from 200,000 km. to 294,000 km. above the sun's surface the rate of ascent of the center of the arch was 37 km. per sec.; at the latter height the velocity abruptly increased to 163.9 km. per sec., which was held for no less than 426,000 km., and was still retained at the disappearance of the projected mass.

However these extraordinary phenomena are to be explained, two significant things are implied: (1) that in some way the gravitation of the sun is offset or neutralized sufficiently to permit uniform motion, so far at least as the projected matter was con-

[1] Edison Pettit, "The Great Eruptive Prominences of May 29 and July 15, 1919," *Astrophys. Jour.*, L (October, 1919), pp. 206–19.



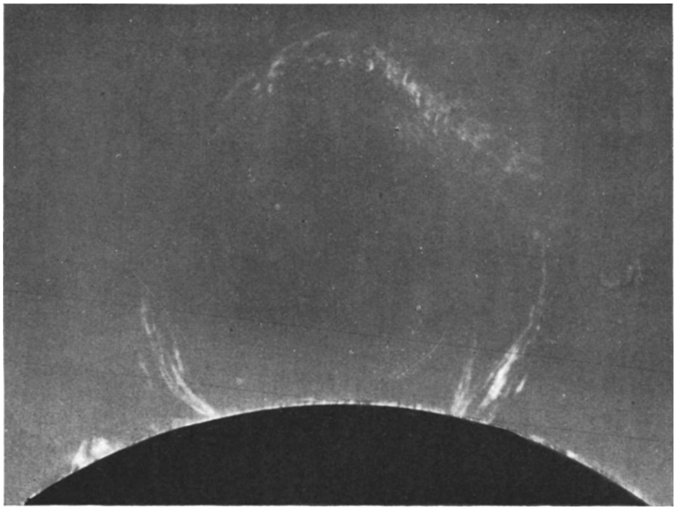
c
G.M.T.
$5^{h}32^{m}41^{s}$

b
$2^{h}56^{m}56^{s}$

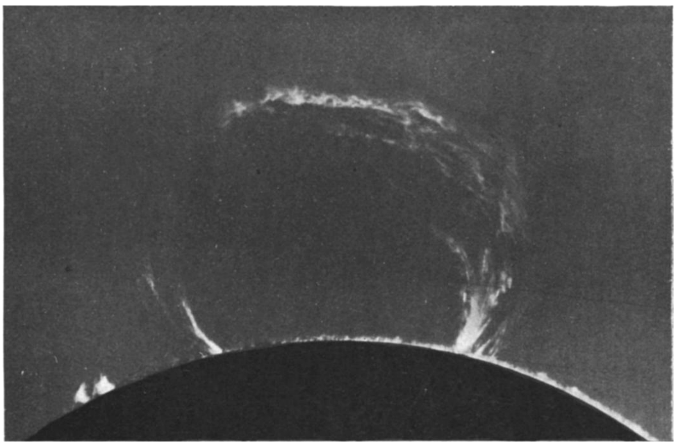
a
$1^{h}41^{m}16^{s}$

THE GREAT PROMINENCE OF MAY 29, 1919
Scale: for *a*, 1mm. = 9,326 km.; for *b* and *c*, 1 mm. = 8,416 km.
(After Pettit)

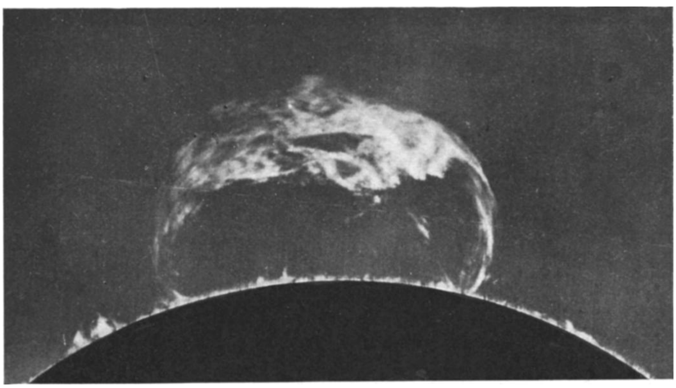
h
G.M.T.
$4^h 7^m 19^s$



g
$3^h 51^m 56^s$



f
$3^h 8^m 2^s$



THE PROMINENCE OF JULY 15, 1919
Scale: 1 mm. = 9,572 km.
(After Pettit)

cerned; and (2) that this matter received successive strong outward impulses, amounting in the last case to an increase of projection no less than 126.9 km. per sec. It is to be noted that this impulse was received after the arch had reached a height of 290,000 km. above the sun's surface. It is further to be observed that at the time the projections became invisible, in each case, more than half the restraining power of the sun, measured in terms of velocity, had been overcome. In the second case, the speed, at the time the projected matter became invisible, was competent to overcome more than half the remainder of the sun's restraining power.

Pettit finds data confirming these strange modes of movement, but of a less conclusive kind, in the photographs of certain other prominences already taken. He regards this singular mode of ascent by sudden accessions of speed with uniform motion between as the common one. However, none of these cases are sufficiently complete in themselves to show the full nature of these remarkable phenomena, for the ejected material passed out of sight while still under the highest observed uniform motion, and the extent to which this uniform motion may have continued and what followed it are left undetermined.

While further disclosures are required, and can only be awaited with eagerness, enough has already been revealed to give radical suggestiveness to these phenomena. They show that even at present and without obvious external stimulus there come into action, in addition to the internal eruptive forces, projectile forces of a high order which became effective at horizons high above the sun's surface, and that the combined projectile effect of these had overcome a large fraction of the restraining power of the sun before they passed out of sight.

Still another feature of the solar eruptions of May 29 and July 15, 1919, is scarcely less remarkable than their singular increments of motion. The projections on each of the two dates took the form of arches whose centers, at first low, rose impulsively into the forms shown on Plates I and II. The arch of May 29 was transverse to the sun's equator and had a chord of 584,000 km.; that of July 15 stood obliquely across the equator and had a chord of 363,000 km. as seen in perspective. The two ends of the arches appear

to have functioned quite differently. At one end, the arches seem to have sprung from short stumplike prominences that had been present for some time before the special eruptions of the dates named and remained for some time afterward. The movements of the calcium clouds near these seemingly originating ends were not only upward but inward toward the center of the arches. At the other end, the arches were apparently related to sun-spots. In these ends of the arches the calcium clouds seemed to be shooting swiftly toward the sun-spots. The photographs appear to show that special features in the upper part of the arches were drifting more or less from the prominence at the originating ends toward the sun-spot ends, though the motion of the central part of the arches was mainly upward. The total motions of the individual calcium molecules seem thus to have embraced a notable lateral component as well as the dominant ascensive one. The discovery by Hale and his associates that the cyclonic whirls associated with the sun-spots are negatively charged may perhaps be made to throw light on this. When ionization takes place by the discharge of an electrical element, it is usually the electron that is shot away, and the residual matter is then commonly positive. If, therefore, it be assumed that the calcium molecules shot forth from the stump prominences were positively charged, they would be drawn toward the negative charges of the sun-spot whirls.

A further feature of much interest is the suggestion of a rotational component in the projectile motion. This is implied in what has just been noted, a lateral movement combined with a vertical movement. A rather distinct expression of rotation seems to be shown in the spiraloid form of the upper central mass shown in Fig. *C*, Plate I. The value of this rotatory movement may be inferred from the fact that this spiraloid cloud had a volume more than 1,000 times that of the earth, assuming that its diameter in the line of vision was equal to the shorter of the two visible diameters.

While all these disclosures must remain *sub judice* until they have been amply verified and their interpretation made sure, it is permissible to bring their suggestiveness into service at once to mitigate the force of old views that always act as a drag upon new

views. These disclosures should help to lessen all hesitation in accepting the view that our atmosphere is even now receiving solar contributions. They should also lessen doubts as to the possibility of the projection of great masses of sun substance to planetary distances whenever stimulus is added to the spontaneous eruptivity of the sun.

MULTIPLE PHASES OF THE PLANETESIMAL HYPOTHESIS

In these new disclosures there is the germ of a new phase of the planetesimal hypothesis, a phase that may possibly dispense with aid from outside the solar system—heretofore supposed to be necessary—and so make the origin of planets a wholly domestic affair, though at present the suggestion does not look very promising. These disclosures seem to make the radial projection of the matter requisite for a planetary system possible without stimulus from outside. At the same time a *transverse* component of the projection is indicated in what has just been said about the lateral movement from the originating end of the arch toward the sun-spot end. If this lateral movement should prove adequate, and also be found to be preponderant in the right direction, it would contribute the component necessary to the revolution of the projected matter. The lateral movements in the two cases observed were chiefly across the equator of the sun, that is, normal to the required effect instead of coincident with it; but the position of the arches transverse to the line of sight in these two cases may be the essential reason why they were observed to such good effect. Similar movements in the line of sight, and in the direction of the sun's rotation, that is, the direction of planetary revolution, may not only be as common as these, but even be the predominant ones.

As the suggestion has only limited plausibility at present, it need not be further deployed here, but as it offers the possibility of a monoecious development of the planetary family in distinction from the dioecious origin heretofore postulated, even the shadow of such hypothesis is welcomed to a place among the multiple working sub-hypotheses that make up the planetesimal genus. Arranged with other developments of like order, the group of such sub-hypotheses embraces the following:

1. *Stimulus to eruptivity, as well as generation of tangential motion in the projected matter assigned to a passing star.*

   a) Star of medium mass and distance (one to five astronomical units, more or less). Original type, tested mathematically by half-hundred concrete trial cases.

   b) Giant star (in mass); distance great, tidal effect small, tangential effect large.

   c) Diminutive star, distance relatively small, tidal effect relatively large, tangential effect relatively small.

2. *Stimulus to eruptivity, as well as generation of tangential motion in the projected matter, assigned to some non-stellar body*, a stray planet for example. Approach to sun quite close, perhaps penetrating its Roche limit; tidal effect relatively great; adequacy of tangential effect less obvious, but assigned to the closeness with which the solar projections were shot out behind the passing body.

3. *Stimulus to eruptivity, as well as generation of tangential motion in the projected matter, assigned to a special concentration of gravitative stress in open space arising from two or more related bodies of large mass*, for example, the center of gravity between two stars, or the concentrated gravity-stress of star clusters in certain forms of arrangement.

4. *Actuating forces arising wholly within the solar system.* Projectile effects assigned to eruptive and projective forces within the sun; the tangential effects assigned to co-operative action of positive and negative centers in the sun as suggested above. Little more than a suggested possibility.

CRITICAL PHASES OF THE EVOLUTIONARY PROCESS

Let us follow that form of the planetesimal hypothesis whose working competency has been most fully tested. According to this the nuclei of the planets and satellites arose from solar eruptions—those of the planets from the central masses of such eruptions, those of the satellites from subsidiary masses that closely accompanied these and kept within their spheres of control. It is our special task to follow the nuclei of the four little bodies under study from their source in the sun to their organized states, having especially in mind those features that bear on the segregation of

heavy from light material, but it will be helpful to keep in mind bodies of both the larger and the smaller orders. So far as the selection and the segregation of matter is concerned, there was no essential difference between the planets and the satellites as such, for each arose from independent portions of the erupted sun substance. The critical elements were the spheres of control dependent on mass and dynamic environment.

While we must await further light on the precise modes in which solar gas-masses are shot forth and the circumstances that induce them, we may be quite sure that, as they passed away from the sun into the outer field of its control, certain influences inevitably affected them. They must have been under the control of a projectile force sufficient to overcome the larger portion of the sun's total attraction. In this controlling force we may safely assume that there were conjoined (1) an original projectile force having its origin in the interior of the sun, (2) radiation pressure from the sun after the mass had left its surface, and (3) electrical effects, attractive and repellent, as also ballistic, that is, due to the momentum of electrons and alpha particles shot forth from the sun and caught by the escaping mass. Just what proportionate parts these co-operating agencies played in the total work of projection, we need not now inquire. It is taken for granted, since it is almost inevitable, that in escaping from the sun the gas-masses acquired some measure of rotatory motion, in addition to the rotation they already had as parts of the sun; there may have been included some measure of vortex motion as most eruptions generate such motion. There can be no question that practically all the constituents of the outbursts were in the gaseous state as they emerged from the sun and that they carried in to the subsequent evolution the molecular activities common to hot gases. The several projectile motions were more or less independently imposed on the emerging mass, and later these underwent more or less independent increases and declines, so that an important part of the ensuing evolution consisted in their mutual adjustment to one another. At the outset, the projectile velocity greatly preponderated over the velocities of all other motions, and until this became adjusted so as to be approximately proportionate to all

integers of the mass it was a prime source of turbulence and danger of dispersion. In so far as molecules were driven by it beyond the sphere of control of the common mass, they took courses of their own and, in the main, either returned by elliptical paths to the sun or became planetesimals. The danger of dispersion at this stage was a serious menace to all the minor masses whose self-control was feeble; at the same time it was a prolific source of planetesimal food for the growth of the nuclei later.

The hypothesis assumes that a part of the out-shot masses contained matter enough to give them self-control. The effectiveness of their control increased as they passed from the more intense to the less intense field of the sun's control, except as they lost material. But such self-control is not postulated of more than a part—probably less than half—the matter projected from the sun, the more scattered portion becoming planetesimals at once or else returning to the sun. Effective self-control is only assigned to a few of the greater eruptions, or, to be specific, to four of the major order, to form the nuclei of the four giant planets, and to four of the minor order, to form the nuclei of the terrestrial planets. But subordinate to these, perhaps a thousand or so little knots succeeded in holding themselves together and later grew into planetoids and satellites. It is thus assumed that there arose, as a result of eruptive projection and partial dispersion, a graded series of knots ranging from those that were massive enough to form the nuclei of the great planets down through medium and smaller knots to masses too small to hold themselves together in the face of the dissipating influences. It was of course in the lower ranges of this graded series that there arose the more critical questions of self-control and of permanent maintenance. The answers to these critical questions hung, in each individual case, very largely upon gravitative competency.

Now we need not dwell on the largest order of knots, for they do not enter our problem. Their strong attractions enabled them to hold their own, except for a small percentage of molecules that attained exceptional cumulative speeds, while, on the other hand, they were able to pick up stray planetesimals that came within their spheres of control in a favorable way. And so in the end,

between their ability to hold all sorts of molecules as well as pick them up, they came to have a much larger proportion of light molecules than the smaller bodies which could only hold the heavier ones, and so they now have relatively low specific gravities. Their great size helped them to remain hot, which also contributed to their low specific gravities. The largest of these is now more than three hundred times as massive as the largest of the terrestrial group; the mean mass of the giant planets is more than two hundred times the mean mass of the terrestrial planets. Our problem then is with a group of distinctly small bodies in which the balance between holding and non-holding power was more critical, and we need to enter somewhat more into detail.

1. As the material was shot forth from the sun, it was an intimate mixture of solar molecules of various kinds in a very hot gaseous form, and the molecules were interacting upon one another at speeds inversely proportional to the square roots of their molecular weights. In the process of forming definite knots under self-control out of the less-defined solar outbursts, of which a considerable part was dissipated into planetesimals or fell back to the sun, the lighter molecules of high speed would be more likely to be dissipated than the heavy ones of lesser speed, but we need not insist on that, as the dispersing danger came from the projectile force and probably was not very selective.

2. But when that contingency was passed and each knot began its own independent evolution, there arose a very definite selective process within the knot itself. We assume that for a short time the knots would still be hot and diffuse, and that during this stage there would be larger chances for molecules to escape from the control of the knot than later (*a*) because their velocities were highest on account of temperature, and (*b*) because their deployment was relatively open so that the molecules were less in one another's way when they happened to accumulate velocity enough to escape from control. We assume that this was the most crucial stage of the knot, and that selective loss was then its greatest danger. The lightest molecules, because they had the highest mean speeds and most frequently encountered and divided energies with other molecules, were those that most often acquired cumulative speeds

enough to enable them to escape. In each encounter there was an equi-partition of energy and the light molecules were given superior speeds in compensation for their lack of mass. The action was thus a highly selective process.

But lest we seem to overstress this depleting process, let it be noted that for every reaction that gave exceptional speed to a light molecule there was a reaction in a counter-direction that gave to the heavier partner in the encounter a lower velocity. And further, it was only in the outer border of the knot that the lighter molecule rebounding outward could usually find a way of escape without another collision and a rebound in the wrong direction, and so the effect of the counter-reaction was to drive a heavier molecule inward for every case in which a lighter molecule escaped. This tended to herd in the heavier molecules and make their mutual attraction more effective, while they were inherently more amenable to control. There was a loss of mass, to be sure, but there was a more than compensating loss of dissipating activity and the residue was more congenial to control.

Taking the knot as a whole, then, there was a steady progress toward a higher average of heavier molecules, and toward an assemblage more amenable to control. Those knots which had been given masses enough to endure this process soon reached a stage of safety and then began to build up by capturing such planetesimals as they could control. Those knots that could not endure the process dispersed into planetesimals or erratic wanderers. The hypothesis, of course, assumes that the nuclei of our four bodies had original masses enough to live through this critical stage, as did also those of all the planetoids and satellites, but it favors the belief that the smallest planetoids and satellites represent the lower limit of successful knots, for if still smaller ones were successful we might expect to see their representatives in the heavens about us. The giant hot stars are, of course, the greatest known examples of success in holding light, hot gases by self-gravity. The multitude of these are our assurance that the principle of gaseous self-control is sound and that it has realization of the highest order in the great cosmos.

It scarcely need be added that the severest selection of heavy molecules would be realized in the smallest knots where the struggle to maintain themselves was most strenuous, and that in the intermediate class the percentage of heavy molecules would be inversely proportional to mass.

All this relates to the purely molecular state assumed to prevail while the knots were organizing themselves out of solar ejections and were beginning their careers as the nuclei of growth into mature planets, planetoids and satellites.

3. Let us turn now to the inner evolution of these nuclei. Let us recall that immediately on the emergence of the gas-masses from the sun there was great expansion and much cooling in consequence. Rapid radiation must have followed as the expanded mass shot out into the relatively cold space of the outer regions. It seems inevitable therefore that the condensation temperatures of the refractory material that now makes up most of the solid body of the earth, and doubtless of its neighbors, would be reached at a succession of stages relatively early in the history of the medium and smaller order of knots. We may assume that the condensation into minute spherules was started by electric charges and followed essentially the lines already sketched in the study of the derivatives from a rotating spheroidal nebula. There was this difference, however. The centrifugal derivatives from the rotating nebula were planetesimals each following its own orbit. The condensations within the nuclei were, at first at least, scattered through the uncondensed portion that was still gaseous. The condensed spherules or crystals were like cloud particles or dust particles in an atmosphere. Dynamically they were like Brownian particles, jostled about by the impacts of the molecules that still remained in the gaseous state. They would naturally develop earliest in the outer parts of the nuclei and later in the inner parts. They would constitute a class of bodies heavier than the molecules and would tend to damp molecular action, while they themselves would tend to fall toward the center of the nuclei, but their fall would be resisted by the part that remained gaseous. It is obvious that the condensation of the refractory heavy material into spherules or

crystals in the midst of the gaseous molecules would mark the turn of the tide in the history of the smaller nuclei for the molecular losses would speedily grow less and a definite centralizing movement would set in which would increase the power of self-control. Molecular losses would be lessened and the capture of planetesimals increased relatively.

The question of the temperatures and the physical states that would follow this stage in the smaller nuclei is important and difficult but must be deferred.

4. It remains only to consider the selective action of the successful nuclei in the process of gathering in planetesimals, but this need not detain us for the principles would be essentially those already emphasized sufficiently. The smaller order of nuclei could not capture and hold the lighter free molecules as such, though they could perhaps capture and retain the very heavy molecules. They could quite certainly hold most of the planetesimal aggregates that they encountered but would have little power to draw them to themselves. The nuclei of medium mass could hold some of the free molecules but not the lightest, and so their accessions would be greater in mass, but lower in mean specific gravity.

SUMMARY

It seems clear, then, from the foregoing considerations that, *in general, the planets, planetoids, and satellites, if built up by the planetesimal method, would be composed of inherently heavy material in inverse proportion to their masses,* and hence that the inherent specific gravity of the matter of the moon would be somewhat greater than that of Mars, that of Mars somewhat greater than that of Venus, and that of Venus greater than that of the earth.

There is still need to consider (1) what were the physical states of the nuclei while they were gathering in the planetesimals, (2) what masses the planetesimals attained, and (3) what was the effect of their infall on the later stages of the growing bodies. This last will obviously involve the frequency of the fall of the planetesimals upon the nuclei. The discussion of these points must be deferred to the next article.

It may be noted, however, that the physical state of the matter, whatever it may be, will not radically affect the mean constitution of the bodies, though it is liable to affect greatly the distribution of the material. Reserving judgment on any shrinkage effect that may arise from such difference of distribution, we may note that the inquiries of this paper, in harmony with the suggestions of the previous paper, very distinctly imply that, if the moon, Mars, Venus, and the earth were built up normally by the planetesimal method, they should contain proportions of inherently heavy material in the inverse order of mass. There is therefore corresponding reason to think that the estimate of the total shrinkage of the earth deduced in the preceding article will need to be somewhat increased, as anticipated, on account of the differences of material that make up the four bodies compared.